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(54) Method and apparatus for measuring a pad profile and closed loop control of a pad conditioning process

(57) A method and apparatus for enhancing the process performance over the life of a polishing pad (120) in a chemical-mechanical polishing apparatus (80) employs closed loop control of polishing pad wear. A contactless displacement sensor (175), such as a laser displacement sensor, provides feedback that is used to generate a pad profile of the polishing pad. Conditioning apparatus (130) is then controlled in response to the feedback from the laser displacement sensor in a closed loop control to modify the conditioning process and control the pad wear uniformity.

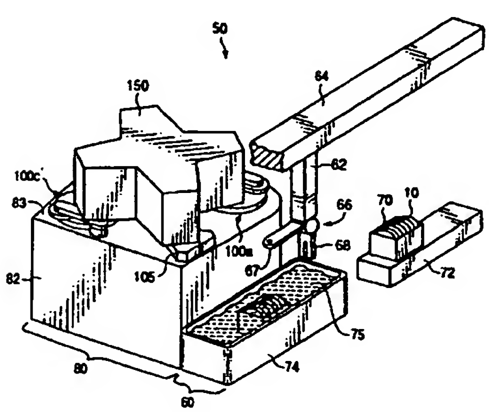

FIG. 3

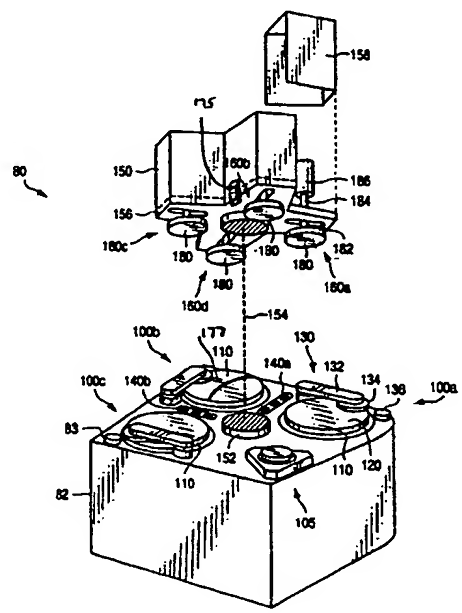

FIG. 4

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Description

[0001] The invention relates to chemical mechanical polishing of substrates, and more particularly to an apparatus for measuring the profile of a polishing pad.

[0002] Integrated circuits are typically formed on substrates, particularly silicon wafers, by the sequential deposition of conductive, semiconductive or insulative layers. After each layer is deposited, the layer is etched to create circuitry features. As a series of layers are sequentially deposited and etched, the outer or uppermost surface of the substrate, i.e., the exposed surface of the substrate, becomes successively more non-planar. This occurs because the distance between the outer surface and the underlying substrate is greatest in regions of the substrate where the least etching has occurred, and least in regions where the greatest etching has occurred. With a single patterned underlying layer, this non-planar surface comprises a series of peaks and valleys wherein the distance between the highest peak and the lowest valley may be on the order of 7000 to 10,000 Angstroms. With multiple patterned underlying layers, the height difference between the peaks and valleys becomes even more severe, and can reach several microns.

[0003] This non-planar outer surface presents a problem for the integrated circuit manufacturer. If the outer surface is non-planar, then photolithographic techniques to pattern photoresist layers might not be suitable, as a non-planar surface can prevent proper focusing of the photolithography apparatus. Therefore, there is a need to periodically planarize this substrate surface to provide a planar layer surface. Planarization, in effect, polishes away a non-planar, outer surface, whether a conductive, semiconductive, or insulative layer, to form a relatively flat, smooth surface. Following planarization, additional layers may be deposited on the outer layer to form interconnect lines between features, or the outer layer may be etched to form vias to lower features.

[0004] Chemical mechanical polishing is one accepted method of planarization. This planarization method typically requires that the substrate be mounted on a carrier or polishing head, with the surface of the substrate to be polished exposed. The substrate is then placed against a rotating polishing pad. In addition, the carrier head may rotate to provide additional motion between the substrate and polishing surface. Further, a polishing slurry, including an abrasive and at least one chemically-reactive agent, may be spread on the polishing pad to provide an abrasive chemical solution at the interface between the pad and substrate.

[0005] Important factors in the chemical mechanical polishing process are: the finish (roughness) and flatness (lack of large scale topography) of the substrate surface, and the polishing rate. Inadequate flatness and finish can produce substrate defects. The polishing rate sets the time needed to polish a layer. Thus, it sets the maximum throughput of the polishing apparatus.

[0006] Each polishing pad provides a surface which, in combination with the specific slurry mixture, can provide specific polishing characteristics. Thus, for any material being polished, the pad and slurry combination is theoretically capable of providing a specified finish and flatness on the polished surface. The pad and slurry combination can provide this finish and flatness in a specified polishing time. Additional factors, such as the relative speed between the substrate and pad, and the force pressing the substrate against the pad, affect the polishing rate, finish and flatness.

[0007] Because inadequate flatness and finish can create defective substrates, the selection of a polishing pad and slurry combination is usually dictated by the required finish and flatness. Given these constraints, the polishing time needed to achieve the required finish and flatness sets the maximum throughput of the polishing apparatus.

[0008] An additional limitation on polishing throughput is "glazing" of the polishing pad. Glazing occurs when the polishing pad is heated and compressed in regions where the substrate is pressed against it. The peaks of the polishing pad are pressed down and the pits of the polishing pad are filled up, so the surface of the polishing pad becomes smoother and less abrasive. As a result, the polishing time required to polish a substrate increases. Therefore, the polishing pad surface must be periodically returned to an abrasive condition, or "conditioned", to maintain a high throughput.

[0009] An additional consideration in the production of integrated circuits is process and product stability. To achieve a low defect rate, each successive substrate should be polished under similar conditions. Each substrate should be polished by approximately the same amount so that each integrated circuit is substantially identical.

[0010] An apparatus for measuring the profile of a polishing pad in a chemical-mechanical polishing system has been described in U.S. Patent 5,875,559. The apparatus generates pad profiles that include the measurement of the thickness of the polishing pad which may be used to optimize the polishing process parameters or to select a conditioning process. The pad profiler generates plots of the surface profile of the polishing pad. These plots may be used by machine operators to select a conditioning process. There is no automatic control or closed loop control of the conditioning process. Hence, if any changes need to be made to the conditioning process based on the surface profiles generated by the pad profiler, these changes would be made in a separate operation by the machine operator.

[0011] One of the primary consumables in the chemical-mechanical polishing process is the pad that is used to polish a wafer. The pad profile changes as a result of the polishing and the conditioning processes. When the pads reach an out-of-range condition such that the desired polishing quality is not producible by the

continued use of the pad, the pad is replaced. It is desirable to control the conditioning of pads to increase the lifetime of the pad.

[0012] In view of the foregoing, there is a need for a chemical-mechanical polishing apparatus that extends the life of polishing pads, reduces human intervention and improves the control of the conditioning process.

[0013] There is a need for a method and apparatus to control the pad conditioning process automatically in order to extend the useable life of a polishing pad in a chemical-mechanical polishing apparatus. There is also a need for accurate detection of the end of usable life of a polishing pad. There is a further need for providing an *in situ* method of measuring the surface profile of a polishing pad of a chemical-mechanical polishing apparatus.

[0014] These and other needs are met by embodiments of the present invention which provide a method of controlling the wear of a polishing pad in which the profile of a polishing surface of a polishing pad is measured. The conditioning of the polishing pad is modified as a function of the measured profile to control the wear of the polishing pad.

[0015] By using the measuring profile to modify the conditioning of a polishing pad, the wear of the polishing pad is controlled, in accordance with embodiments of the present invention, and thereby extension of the usable life of the polishing pad may be achieved. The controlling of the wear of the polishing pad and the modifying of the conditioning of the polishing pad in a closed loop manner as a function of the measured profile provides an automatic control and enhances throughput of the wafers. This is in contrast to the prior art methods in which a measuring device was placed over a polishing pad after stopping operation of the polishing apparatus so that measurements can be taken. Also, the modification of the polishing pad conditioning process was not performed in a closed loop manner in the prior art.

[0016] The earlier stated needs are also meet by another embodiment of the present invention which provides a method of detecting an end of useable life of a polishing pad in a chemical-mechanical polishing apparatus that includes the steps of transferring a workpiece from a polishing station that has a polishing pad on which the workpiece is polished, and measuring wear of the polishing pad during transferring of the workpiece. The wear of the polishing pad is compared to a threshold wear amount to determine when the end of useable life of the polishing pad has been reached.

[0017] One of the advantages of the present invention is the increased throughput provided by the act of measuring the wear of the polishing pad during the transfer of the workpiece. This is an improvement over methods which halted operation on the chemical-mechanical polishing apparatus to check the wear of the polishing pad. The method lends itself to automatic operation, thereby reducing human intervention and therefore costs.

[0018] The arrangements are also met by another embodiment of the present invention which provides an arrangement for measuring the condition of a polishing pad in a chemical-mechanical polishing apparatus. The arrangement includes a carousel that transports workpieces to be polished to and from a polishing pad. The arrangement also includes a contactless displacement sensor that is mounted to traverse above at least a portion of the polishing pad when the carousel transports workpieces to and from a polishing pad. The sensor makes displacement measurements at a plurality of points on a polishing pad to determine the condition of the polishing pad. A controller is responsive to the displacement measurements to modify a polishing pad conditioning process.

[0019] The arrangement of the present invention has the advantage of using a contactless displacement sensor that may be mounted in any of a number of different manners to traverse the polishing pad and take displacement measurements in a contactless manner. This also allows the arrangement to be used in an *in situ* manner during operation of the polishing apparatus. Throughput is increased since the displacement measurements are taken during the transportation of the workpieces to and from the polishing pad by the carousel. The useable life of the polishing pad may be extended by the response of the controller to the displacements measurements to modify the polishing pad conditioning process.

[0020] Additional advantages of the present invention will become readily apparent to those skilled in this art from the following detailed description. wherein embodiments of the present invention are described, simply by way of illustration of the best mode contemplated for carrying out the present invention. As will be realized, the present invention is capable of other and different embodiments, and its several details are capable of modifications in various obvious respects, all without departing from the present invention. Accordingly, the drawings and description are to be regarded as illustrative in nature, and not as restrictive.

FIGS. 1A-1E are schematic diagrams illustrating the deposition and etching of a layer on a substrate.

FIGS. 2A-2C are schematic diagrams illustrating the polishing of a non-planar outer surface of a substrate.

FIG. 3 is a schematic perspective view of a chemical mechanical polishing apparatus.

FIG. 4 is a schematic exploded perspective view of the chemical mechanical polishing apparatus of FIG. 3.

FIGS. 5A-5F are schematic top views of the polishing apparatus illustrating the progressive movement of wafers as they are sequentially loaded and polished.

FIG. 6 is a schematic side view of a polishing pad.

FIG. 7 is a schematic perspective view, with a partial cross section, of a worn polishing pad.

FIG. 8 is a schematic block diagram of a computer control system for the pad profiler and pad conditioning controller of the present invention.

FIG. 9 is a top view of a disk with a depiction of zones of the disk.

FIG. 10 is a flow chart of an exemplary embodiment of the method of the present invention to modify the pad conditioning process.

FIGS. 11A-11C are schematic graphics illustrating pad profile measurements

[0021] FIGS. 1A-1E illustrate the process of depositing a layer onto a planar surface of a substrate. As shown in FIG. 1A, a substrate 10 might be processed by coating a flat semiconductive silicon wafer 12 with a metal layer 14, such as aluminum. Then, as shown in FIG. 1B, a layer of photoresist 16 may be placed on metal layer 14. Photoresist layer 16 can then be exposed to a light image, as discussed in more detail below, producing a patterned photoresist layer 16' shown in FIG. 1C. As shown in FIG. 1D, after patterned photoresist layer 16' is created, the exposed portions of metal layer 14 are etched to create metal islands 14'. Finally, as shown in FIG. 1E, the remaining photoresist is removed.

[0022] FIGS. 2A-2B illustrate the difficulty presented by deposition of subsequent layers on a substrate. As shown in FIG. 2A, an insulative layer 20, such as silicon dioxide, may be deposited over metal islands 14'. The outer surface 22 of insulative layer 20 almost exactly replicates the underlying structures of the metal islands, creating a series of peaks and valleys so outer surface 22 is non-planar. An even more complicated outer surface would be generated by depositing and etching multiple layers on an underlying patterned layer.

[0023] If, as shown in FIG. 2B, outer surface 22 of substrate 10 is non-planar, then a photoresist layer 25 placed thereon is also non-planar. A photoresist layer is typically patterned by a photolithographic apparatus that focuses a light image onto the photoresist. Such an imaging apparatus typically has a depth of focus of about 0.2 to 0.4 microns for sub-halfmicron feature sizes. If the photoresist layer 25 is sufficiently non-planar, that is, if the maximum height difference h between a peak and valley of outer surface 22 is greater than the depth of focus of the imaging apparatus, then it will be impossible to properly focus the light image onto the entire surface 22. Even if the imaging apparatus can accommodate the non-planarity created by a single underlying patterned layer, after the deposition of a sufficient number of patterned layers, the maximum height difference will exceed the depth of focus.

[0024] It may be prohibitively expensive to design new photolithographic devices having an improved depth of a focus. In addition, as the feature size used in integrated circuits becomes smaller, shorter wavelengths of light must be used, resulting in further reduction of the available depth of focus.

[0025] A solution, as shown in FIG. 2C, is to planarize the outer surface. Planarization wears away the outer surface, whether metal, semiconductive, or insulative, to form a substantially smooth, flat outer surface 22. As such, the photolithographic apparatus can be properly focused. Planarization could be performed only when necessary to prevent the peak-to-valley difference from exceeding the depth of focus, or planarization could be performed each time a new layer is deposited over a patterned layer.

[0026] Polishing may be performed on metallic, semiconductive, or insulative layers. The particular reactive agents, abrasive particles, and catalysts will differ depending on the surface being polished. The present invention is applicable to polishing of any of the above layers.

[0027] As shown in FIG. 3, a chemical-mechanical polishing system 50 according to the present invention includes a loading apparatus 60 adjacent to a polishing apparatus 80. Loading apparatus 60 includes a rotatable, extendable arm 62 hanging from an overhead track 64. In the figure, overhead track 64 has been partially cut-away to more clearly show polishing apparatus 80. Arm 62 ends in a wrist assembly 66 which includes a blade 67 with a vacuum port and a cassette claw 68.

[0028] Substrates 10 are brought to polishing system 50 in a cassette 70 and placed on a holding station 72 or directly into a tub 74. Cassette claw 68 on arm 62 may be used to grasp cassette 70 and move it from holding station 72 to tub 74. Tub 74 is filled with a liquid bath 75, such as deionized water. Blade 67 fastens to an individual substrate from cassette 70 in tub 74 by vacuum suction, removes the substrate from cassette 70, and loads the substrate into polishing apparatus 80. Once polishing apparatus 80 has completed polishing the substrate, blade 67 returns the substrate to the same cassette 70 or to a different one. Once all of the substrates in cassette 70 are polished, claw 68 may remove cassette 70 from tub 74 and return the cassette to holding station 72.

[0029] Polishing apparatus 80 includes a lower machine base 82 with a table top 83 mounted thereon and removable upper outer cover (not shown). As best seen in FIG. 4, table top 83 supports a series of polishing stations 100a, 100b and 100c, and a transfer station 105. Transfer station 105 forms a generally square arrangement with the three polishing stations 100a, 100b and 100c. Transfer station 105 serves multiple functions of receiving individual substrates 10 from loading apparatus 60, washing the substrates, loading the substrates into carrier heads (to be described below), receiving the substrates from the carrier heads, washing the substrates again, and finally transferring the substrates back to loading apparatus 60 which returns the substrates to the cassette.

[0030] Each polishing station 100a, 100b, or 100c

includes a rotatable platen 110 on which is placed a polishing pad 120. Each polishing station 100a, 100b and 100c may further include an associated pad conditioner apparatus 130. Each pad conditioner apparatus 130 has a rotatable arm 132 holding an independently rotating conditioner head 134 and an associated washing basin 136. The conditioner apparatus maintains the condition of the polishing pad so it will effectively polish any substrate pressed against it while it is rotating.

[0031] Two or more intermediate washing stations 140a and 140b are positioned between neighboring polishing stations 100a, 100b, 100c and transfer station 105. The washing stations rinse the substrates as they pass from one polishing station to another.

[0032] A rotatable multi-head carousel 150 is positioned above lower machine base 82. Carousel 150 is supported by a center post 152 and rotated thereon about a carousel axis 154 by a carousel motor assembly located within base 82. Center post 152 supports a carousel support plate 156 and a cover 158.

[0033] Multi-head carousel 150 includes four carrier head systems 160a, 160b, 160c, and 160d. Three of the carrier head systems receive and hold a substrate, and polish it by pressing it against the polishing pad 120 on platen 110 of polishing stations 100a, 100b and 100c. One of the carrier head systems receives substrates from and delivers substrates to transfer station 105.

[0034] In the preferred embodiment, the four carrier head systems 160a-160d are mounted on carousel support plate 156 at equal angular intervals about carousel axis 154. Center post 152 supports carousel support plate 156 and allows the carousel motor to rotate the carousel support plate 156 and to orbit the carrier head systems 160a-160d, and the substrates attached thereto, about carousel axis 154.

[0035] Each carrier head system 160a-160d includes a polishing or carrier head 180. Each carrier head 180 independently rotates about its own axis, and independently laterally oscillates in a radial slot 182 formed in support plate 156. A carrier drive shaft 184 connects a carrier head rotation motor 186 to carrier head 180 (shown by the removal of one-quarter of cover 158). There is one carrier drive shaft and motor for each head.

[0036] The substrates attached to the bottom of carrier heads 180 may be raised or lowered by the polishing head systems 160a-160d. An advantage of the overall carousel system is that only a short vertical stroke is required of the polishing head systems to accept substrates, and position them for polishing and washing. An input control signal (e.g., a pneumatic, hydraulic, or electrical signal), causes expansion or contraction of carrier head 180 of the polishing head systems in order to accommodate any required vertical stroke. Specifically, the input control signal causes a lower carrier member having a wafer receiving recess to move vertically relative to a stationary upper carrier member.

[0037] During actual polishing, three of the carrier heads, e.g., those of polishing head systems 160a-160c, are positioned at and above respective polishing stations 100a-100c. Each rotatable platen 110 supports a polishing pad 120 with a top surface which is wetted with an abrasive slurry. Carrier head 180 lowers a substrate to contact polishing pad 120, and the abrasive slurry acts as the media for both chemically and mechanically polishing the substrate or wafer.

[0038] After each substrate is polished, polishing pad 120 is conditioned by conditioning apparatus 130. Arm 132 sweeps conditioner head 134 across polishing pad 120 in an oscillatory motion generally between the center of polishing pad 120 and its perimeter. Conditioner head 134 includes an abrasive surface, such as a nickel-coated diamond surface. The abrasive surface of conditioner head 134 is pressed against rotating polishing pad 120 to abrade and condition the pad.

[0039] In use, the polishing head 180, for example, that of the fourth carrier head system 160d, is initially positioned above the wafer transfer station 105. When the carousel 150 is rotated, it positions different carrier head systems 160a, 160b, 160c, and 160d over the polishing stations 100a, 100b and 100c, and the transfer station 105. The carousel 150 allows each polishing head system to be sequentially located, first over the transfer station 105, and then over one or more of the polishing stations 100a- 100c, and then back to the transfer station 105.

[0040] FIGS. 5A-5F show the carrousel 150 and its movement with respect to the insertion of a substrate such as a wafer (W) and subsequent movement of carrier head systems 160a-160d. As shown in FIG. 5A, a first wafer W#1 is loaded from loading apparatus 60 into transfer station 105, where the wafer is washed and then loaded into a carrier head 180, e.g., that of a first carrier head system 160a. Carousel 150 is then rotated counter-clockwise on supporting center post 152 so that, as shown in FIG. 5B, first carrier head system 160a with wafer W#1 is positioned at the first polishing station 10a, which performs a first polish of wafer W#1. While first polishing station 100a is polishing wafer W#1, a second wafer W#2 is loaded from loading apparatus 60 to transfer station 105 and from there to a second carrier head system 160b, now positioned over transfer station 105. Then carousel 150 is again rotated counter-clockwise by 90 degrees so that, as shown in FIG. 5C, first wafer W#1 is positioned over second polishing station 100b and second wafer W#2 is positioned over first polishing station 100a. A third carrier head system 160c is positioned over transfer station 105, from which it receives a third wafer W#3 from loading system 60. In a preferred embodiment, during the stage shown in FIG. 5C, wafer W#1 at second polishing station 100b is polished with a slurry of finer grit than wafer W#1 at the first polishing station 100a. In the next stage, as illustrated by FIG. 5D, carousel 150 is again rotated counter-clockwise by 90 degrees so as to position wafer W#1 over

third polishing station 100c, wafer W#2 over second polishing station 100b, and wafer W#3 over first polishing station 100a, while a fourth carrier head system 160d receives a fourth wafer W#4 from loading apparatus 60. The polishing at third polishing station 100c is presumed to be even finer than that of second polishing station 100b. After the completion of this stage, carousel 150 is again rotated. However, rather than rotating it counter-clockwise by 90 degrees, carousel 150 is rotated clockwise by 270 degrees. By avoiding continuous rotation in one direction, carousel 150 may use simple flexible fluid and electrical connections rather than complex rotary couplings. The rotation, as shown in FIG. 5E, places wafer W#1 over transfer station 105, wafer W#2 over third polishing station 100c, wafer W#3 over second polishing station 100b, and wafer W#4 over first polishing station 100a. While wafers W#1-W#3 are being polished, wafer W#1 is washed at transfer station 105 and returned from carrier head system 160a to loading apparatus 60. Finally, as illustrated by FIG. 5F, a fifth wafer W#5 is loaded into first carrier head system 160a. After this stage, the process is repeated.

[0041] As shown in FIG. 6, a carrier head system, such as system 160a, lowers substrate 10 to engage a polishing station, such as polishing station 100a. As noted, each polishing station includes a rigid platen 110 supporting a polishing pad 120. If substrate 10 is an eight-inch (200 mm) diameter disk, then platen 110 and polishing pad 120 will be about twenty inches in diameter. Platen 110 is preferably a rotatable aluminum or stainless steel plate connected by stainless steel platen drive shaft (not shown) to a platen drive motor (not shown). For most polishing processes, the drive motor rotates platen 120 at thirty to two-hundred revolutions per minute, although lower or higher rotational speeds may be used.

[0042] Polishing pad 120 is a hard composite material with a roughened surface 122. Polishing pad 120 may have a fifty mil thick hard upper layer 124 and a fifty mil thick softer lower layer 126. Upper layer 124 is preferably a material composed of polyurethane mixed with other fillers. Lower layer 126 is preferably a material composed of compressed felt fibers leached with urethane. A common two-layer polishing pad, with the upper layer composed of IC-1000 and the lower layer composed of SUBA-4, is available from Rodel, Inc., located in Newark, Del. (IC-1000 and SUBA-4 are product names of Rodel, Inc.). In one embodiment, polishing pad 120 is attached to platen 110 by a pressure-sensitive adhesive layer 128.

[0043] Each carrier head system includes a rotatable carrier head. The carrier head holds substrate 10 with the top surface 22 pressed face down against outer surface 122 of polishing pad 120. For the main polishing step, usually performed at station 100a, carrier head 180 applies a force of approximately four to ten pounds per square inch (psi) to substrate 10. At subsequent stations, carried head 180 may apply more or less force. For example, for a final polishing step, usually performed at station 100c, carrier head 180 applies about three psi. Carrier drive motor 186 (see FIG. 4) rotates carrier head 180 at about thirty to two-hundred revolutions per minute. In a preferred embodiment, platen 110 and carrier head 180 rotate at substantially the same rate.

[0044] A slurry 190 containing a reactive agent (e.g., deionized water for oxide polishing), abrasive particles (e.g., silicon dioxide for oxide polishing) and a chemically reactive catalyzer (e.g., potassium hydroxide for oxide polishing), is supplied to the surface of polishing pad 120 by a slurry supply tube 195. Sufficient slurry is provided to cover and wet the entire polishing pad 120.

[0045] Chemical-mechanical polishing is a fairly complex process, and differs from simple wet sanding. In a polishing process the reactive agent in slurry 190 reacts with the surface 22 of top layer 20, which may be a conductive, semiconductive, or insulative layer, and with the abrasive particles to form reactive sites. The interaction of the polishing pad, abrasive particles, and reactive agent with the substrate results in polishing.

[0046] As mentioned above, the surface of polishing pad 120 becomes "glazed" during the chemical mechanical polishing process. This glazing is primarily caused by pressure and heat applied to the portion of the pad beneath the carrier head. The heat (about 70°C for IC-1000) causes the polishing pad to lose its rigidity and flow so that, under pressure, the peaks flatten out and the depressions fill up. A glazed polishing pad has a lower coefficient of friction, and thus a substantially lower polishing rate, than a "fresh" or un-glazed pad. As the polishing rate drops, the time required to polish a substrate increases, and the throughput of substrates through the polishing apparatus falls. In addition, because the polishing pad becomes slightly more glazed after each successive polishing operation, each successive substrate may be polished to a slightly different extent. Therefore, the polishing pad must be periodically conditioned to provide a consistently rough pad surface.

[0047] Conditioning deforms the surface of the polishing pad so that it is no longer planar. The conditioning process physically abrades surface 122 of polishing pad 120 to restore its roughness (see FIG. 7). This abrasion "wears" the pad; i.e., it removes material from the surface of the polishing pad. The wear on the polishing pad is often non-uniform. This is because conditioning apparatus 130 (see FIG. 3) may remove more material from polishing pad 120 in some regions than in others.

[0048] The non-uniform thickness of the pad affects the substrate polishing rate. When surface 22 of substrate 10 (see FIG. 6) is pushed against surface 122 of polishing pad 120, the thinner areas of the polishing pad are compressed less, and therefore exert less pressure on substrate 10. Consequently, the thinner areas of the polishing pad will polish a substrate at a slower rate

than the thicker areas. Therefore, the non-uniform thickness of a polishing pad may generate a non-uniform substrate outer layer.

[0049] An unused polishing pad usually has a flat surface. However, as shown schematically by FIG. 7, a used polishing pad 120 has a thickness "t" that varies across the diameter "d" of the polishing pad. A polishing pad typically wears more in a ring area 121 than at the center 123 or edge 125 of the polishing pad. The radius of ring 121 is about half the radius "R" of the polishing pad.

[0050] Conditioning apparatus 130 eventually wears away polishing pad 120 until it is too thin to effectively polish. However, the polishing pad is usually discarded, due to non-uniformities, long before it is worn away. A typical polishing pad has a lifetime of about three-hundred and fifty wafers, assuming the pad is conditioned after each wafer is processed.

[0051] Because the polishing pad rotates, the conditioning and polishing processes tend to create a radially symmetric wear pattern, as shown in FIG. 7. Since the thickness of the pad is radially symmetric, the operator of a polishing apparatus may evaluate a conditioning process by measuring the pad profile, which is the pad thickness along a diameter. The operator can measure the profile after a number n, e.g., one to twenty, conditioning operations to determine which parts of the pad have degraded the most and whether the wear rate has changed. In prior art methods, an operator tries to find the "best" conditioning process, i.e., the conditioning process that creates the least non-uniformity in pad thickness, by comparing the pad profiles of polishing pads subjected to different conditioning processes.

[0052] In addition, an operator can compensate for non-planarity or non-uniformity in the polishing pad by appropriately selecting polishing processing parameters, such as the pressure applied to the substrate, the polishing pad rotation rate, the substrate rotation rate, and the dwell time, which is the duration that a substrate remains at a specific pad location. For example, by selectively sweeping a substrate over both thick and thin regions of the pad, a substrate outer layer may be substantially evenly polished. Alternately, an operator always has the option of simply discarding the polishing pad if the variation in thickness across its surface 122 exceeds some predetermined value.

[0053] Although it is possible for an operator to evaluate a conditioning process by measuring the pad profile, as described above, the present invention provides an automatic measuring process and closed loop control of the pad conditioning process. This increases the throughput from the wafers through the chemical-mechanical polishing process, and reduces the need for human intervention and tweaking of the conditioning process.

[0054] Referring back to FIG. 4, the present invention employs a contactless sensor, such as a laser displacement sensor or ultrasonic displacement sensor, reference numeral 175, that measures the polishing pad profile. In the embodiment depicted in FIG. 4, the displacement sensor 175 is mounted on the carousel 150 in such a manner that it will traverse the upper surface of the polishing pad 120 as the carousel 150 is rotated. In alternative arrangements, the displacement sensor 175 is mounted on an arm which is attached to the table top by a rotatable base so that it may traverse the upper surface of the polishing pad 120 in synchronism with the movement of the transfer of the wafer from polishing pad 120 to another polishing pad 120.

[0055] The mounting of the displacement sensor 175 on the carousel 150 provides an advantage of being able readily move the displacement sensor 175 over each of the different polishing pads 120 and different polishing stations. An exemplary path along which the displacement sensor moves across a polishing pad surface 120 is depicted as reference numeral 177 in FIG. 4. By traversing above and across each of the different polishing pads 120 of the multiple polishing stations of the chemical-mechanical polishing apparatus, a single displacement sensor 175 can successfully measure the pad profile of each of the different polishing pads 120.

[0056] By using a contactless sensor, the present invention avoids the need for separate mounting of an apparatus that will interfere with a polishing operation. The profiling of the pad can therefore be performed *in situ*, and especially during the transfer of the wafer from polishing station to polishing station. In certain preferred embodiments of the invention, the measurements of the pad profile are taken only at specified conditioning intervals. For example, each pad may be measured after twenty conditioning operations to determine the pad profile and to check whether the end of useable life has been reached. This interval may be increased or decreased, either as a preset number or during operation in a dynamic fashion in order to check the pad more often as the pad is being worn more rapidly toward the end of the useable life of the pad.

[0057] FIG. 8 depicts a schematic block diagram of an exemplary control system (i.e., controller) employed in embodiments of the present invention to provide a closed loop control of the conditioning of polishing pads, as well as detect the end of useable life of the polishing pad. The controller 200 includes a CPU 210, an input/output section 212, a memory 214, a monitor 220, and an operator input device 222. The input device 222 may be any of a combination of keyboard, touch screen, mouse, or other commonly employed input devices.

[0058] The input/output 212 provides communication between the controller 200 and the displacement sensor 175 and the conditioning apparatuses 130. The memory 214 contains software that controls the conditioning apparatuses 130, as well as the detection of the end of useable life of a polishing pad. These are logically depicted as programs 216, 218 within the memory

214. However, it should apparent that such programs may be retrieved from a removable storage medium, such as a CD-ROM. For purposes of illustration, however, the conditioning disk control program is depicted as block 216 within memory 214, and the end of useable life software is depicted as block 218 in memory 214.

[0059] Referring now to FIG. 10, an exemplary embodiment of a method of operation of the controller 200 is depicted. At step 300, the wafers are polished as described above at the various polishing stations. At step 302, it is then decided whether the specified number of conditionings has occurred, for example, 20 conditioning cycles with respect to a particular polishing pad 120. If the number of conditioning cycles is less than n, e.g., less than 20, the wafer is transferred without a measurement of the pad profile, as reflected in step 304. Transference of the wafer from station to station is performed as described earlier with respect to Figs. 5A-5F, or in another appropriate manner. Following the transfer of the wafers, without performing a measurement of the pad profile, the pad is then conditioned in accordance with the conditioning process currently in place, as shown in step 306. The conditioning processes are temporarily stored in memory 214 in the software 216 of the conditioning disk control.

[0060] Once any particular polishing station has been conditioned n times, as determined in step 302. a displacement measurement is performed in a contactless manner during the transfer of the wafer that has just been polished to another station. This is shown in step 308. The sensor 175 provides its displacement measurements through the input/output 212 and to the CPU 210. Based on the displacement measurements, it is then determined whether the wear of the pad 120 is greater than a threshold wear amount, as determined in step 310. If the wear is greater than the threshold amount, indicating the end of useable life of the polishing pad 120, the operator is alerted in step 312 to replace the polishing pad 120. Once polishing pad 120 has been replaced, polishing may resume as in step 300.

[0061] Assuming that the displacement measurements and comparison show that the wear of the polishing pad 120 has not exceeded the threshold wear amount, (step 310), the profile of the pad is generated in step 314 by the CPU 210. This may be displayed in the monitor 220 for the operator to review. However, the pad conditioning process is automatically modified in response to the pad profile in step 316. The conditioning process may be modified in any of a number of different ways, such as by changing the pressure of the conditioning disk 134 against the polishing pad 120, the rate of rotation of the polishing pad 120 or the conditioning disk 134, and in preferred embodiments, changing the relative dwell times of the conditioning disk 134 over specific zones of the polishing pad 120. This will be described in more detail later.

[0062] Once the conditioning process has been modified in the conditioning disk control logic 216 within the memory 214, the operation of the conditioning apparatus 130 is modified so that further conditioning is performed in accordance with the modified process. Hence, the method of the present invention proceeds to step 306 from step 316 and the pad is conditioned in accordance with the now-modified conditioning process. Following the conditioning of the polishing pad 120, in accordance with the measured pad profile and modified conditioning process, a new wafer may be polished on the polishing pad 120 in step 300.

[0063] A schematic depiction of the top view of a polishing pad is provided in Fig. 9. The polishing pad 120 is logically divided into radial zones. The number of zones may vary, such as between 5 and 20 zones. In the illustrated embodiment, the pad 120 divided into 5 zones. Assume that the pad profiling performed according to the above-described method indicates that the wear of the polishing pad in zone 4 is greater than the wear in zones 1-3 and 5. Also assume that even wear of the polishing pad throughout the five zones is desirable. The relative dwell times of the conditioning disk 134 on the polishing pad 120 over the different zones may be changed from an equal 20% over each zone to 40% over zone 4 and 15% over each of zones 1-3 and 5. This would cause zone 4 to be worn by the conditioning apparatus 130 at a faster rate than zones 1-3 and zone 5. The change in relative dwell time has the effect of producing a more evenly worn surface on the polishing pad 120.

[0064] The above example is for description purposes only, as the number of zones may change, the relative dwell times may be different, and the changes in the conditioning apparatus operation may be different in other embodiments. For example, instead of changing the relative dwell times, the pressure applied against the polishing pad by the conditioning disk 134 may be changed. However the conditioning process is modified, according to the closed loop control of the present invention, a conditioning may be performed that extends the usable life of the polishing pad 120 in an automatic manner. At the same time, the closed loop control of the present invention increases the throughput over prior methods of measuring the pad profile in which the polishing apparatus operation was halted in order to perform the pad profile measurements. Also, the closed loop control increases throughput since the profile generated by the CPU 210 does not need to be interpreted by an operator and the conditioning process does not have to be modified by an operator.

[0065] In order to generate a pad profile, sensor 175 scans across a radius, such as a radial segment 177 (see FIG. 4), of the top surface of the fresh polishing pad. As it is assumed that the wear pattern of the polishing pad is radially symmetric, measurements taken along radial segment 177 are assumed to represent the pad profile across the entire polishing pad. The

scan results are saved as a baseline file in memory 214. After a number n of polishing operations, the pad profiler 200 scans the worn polishing pad and saves the results as a measurement file. Because the difference between the position measurements of the fresh and worn pad is the change in pad thickness, the computer system 200 subtracts the baseline scan from the measurement scan to produce the pad wear profile. Sensor 175 may perform subsequent measurement scans after a predetermined number of polishing and conditioning processes as to create a series of measurement scans. In such a case, computer system 200 subtracts the original baseline scan from each measurement scan to generate a series of pad profiles. The series of pad profiles may be displayed to show the dynamic wear of a polishing pad.

[0066] Examples of a baseline scan and a measurement scan and a resulting pad profile are illustrated in FIGS. 11A-11B, in which position along radial segment 177 is on the x-axis and the sensor is on the y-axis. An example of a resulting pad profile is illustrated in FIG. 11C, in which the position along radial segment 177 is on the x-axis and the change in pad thickness is on the y-axis. As shown in FIG. 11A, if movement at the sensor 175 is not exactly parallel to the surface of fresh polishing pad 120, then as sensor 175 traverses the pad, it will generate a linear sloped response 450. As shown in FIG. 11B, if a used polishing pad is on the platen, sensor 175 will generate a non-linear response 455. To determine the thickness of the pad as a function of distance along radial segment 177, response 450 is subtracted from response 455 to create pad profile 460. In this example, pad profile 460 shows that polishing pad 120 is thinnest in a ring located at about half the radius of the polishing pad (see FIG. 7).

[0067] An example of a contactless displacement sensor that may be used as the sensor 175 in the present invention is the microtrak 7,000 laser displacement sensor, produced by Mechanical Technology, Inc. This is exemplary only, however, as other models of displacement sensors, as well as other types of displacement sensors, such as ultrasonic sensors, may be used without departing from the invention.

[0068] Although the present invention has been described and illustrated in detail, it is to be clearly understood that the same is by way of illustration and example only and is not to be taken by way of limitation, the scope of the present invention being limited only by the terms of the appended claims.

Claims

1. A method of controlling wear of a polishing paid in a chemical-mechanical polishing apparatus, comprising the steps of:

    measuring a profile of a polishing surface of a polishing pad; and

    modifying conditioning of the polishing pad in a closed loop manner as a function of the measured profile to control the wear of the polishing pad.

2. A method as claimed in claim 1, wherein the step of modifying includes controlling with relative dwell times of a conditioning disk over regions of the polishing pad.

3. A method as claimed in claim 2, further comprising increasing relative dwell times in regions of the polishing pad having polishing surface profiles with less wear than other regions of the polishing pad.

4. The method of claim 3, wherein the modifying of the conditioning of the polishing pad is controlled in a closed loop manner in response to the measuring of the profile of the polishing pad by laser detection.

5. A method as claimed in any of claims 1 to 4, wherein the step of modifying includes controlling pressure of a conditioning disk against regions of the polishing pad.

6. A method as claimed in any of claims 1 to 5, wherein the step of measuring includes measuring the profile of the polishing pad by laser detection.

7. A method as claimed in claim 6, wherein the modifying of the conditioning of the polishing pad is controlled in a closed loop manner in response to the measuring of the profile of the polishing pad by laser detection.

8. A method as claimed in claim 6 or claim 7, wherein the laser detection includes positioning the laser above the polishing pad such that the laser energy generated by the laser impinges on the polishing surface.

9. A method as claimed in claim 8, wherein the laser detection further includes moving the laser relative to the polishing pad such that the laser energy sweeps across at least the radius of the polishing pad.

10. A method as claimed in claim 9, wherein the laser is mounted on a carousel, and the step of moving includes rotating the carousel such that the laser is moved across the polishing pad.

11. A method of detecting an end of useable life of a polishing pad in a chemical-mechanical polishing apparatus, comprising the steps of:

    transferring a workpiece from a polishing station that has a polishing pad on which the work-

piece is polished;
measuring wear of the polishing pad during the transferring of the workpiece;
comparing the wear to a threshold wear amount to determine when the end of useable life of the polishing pad has been reached.

12. A method as claimed in claim 11, wherein the step of measuring the wear includes measuring with a laser displacement sensor the distances from the laser displacement sensor to the polishing paid at a plurality of points across at least a portion of the polishing pad.

13. A method as claimed in claim 12, wherein the step of measuring the wear includes moving the laser displacement sensor relative to the polishing pad.

14. A method as claimed in claim 12 or claim 13, wherein the transferring is performed by a rotatable carousel, and the laser displacement sensor is attached to the carousel to rotate with the carousel such that the laser displacement sensor moves over the polishing pad during the transferring of the workpiece.

15. An apparatus for measuring the condition of a polishing pad of a chemical-mechanical polishing apparatus, comprising:

a carousel that transports workpieces to be polished to and from a polishing pad;
a contactless displacement sensor mounted to traverse above at least a portion of a polishing pad when the carousel transports workpieces to and from the polishing pad and made displacement measurements at a plurality of points on the polish pad to determine the condition of the polishing pad; and
a controller responsive to the displacement measurements to modify a polishing pad conditioning process.

16. The apparatus as claimed in claim 15, wherein the contactless displacement sensor is a laser displacement sensor.

17. The apparatus as claimed in claim 15, wherein the controller is coupled to receive displacement measurements from the laser displacement sensor and generate a surface profile of the polishing pad.

18. The apparatus as claimed in claim 17, further comprising conditioning apparatus that controllably conditions the polish pad, the controller being configured to control the conditioning apparatus as a function of the surface profile of the polishing pad.

19. The apparatus as claimed in claim 18, wherein the conditioning apparatus includes a conditioning disk that contacts and conditions zones of the polishing pad, and when relative dwell times of the conditioning disk on the zones of the polishing pad are controlled by the controller as a function of the surface profile of the polishing pad.

20. The apparatus as claimed in any of claims 15 to 19, wherein the controller is configured to control the conditioning disks in a closed loop manner.

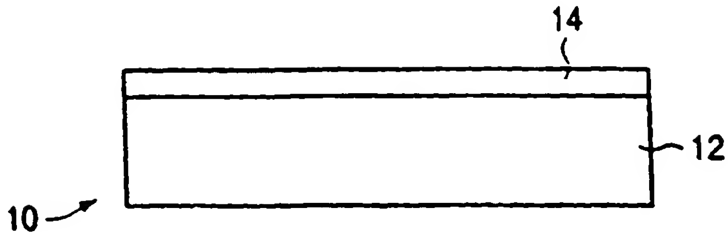


FIG. 1A

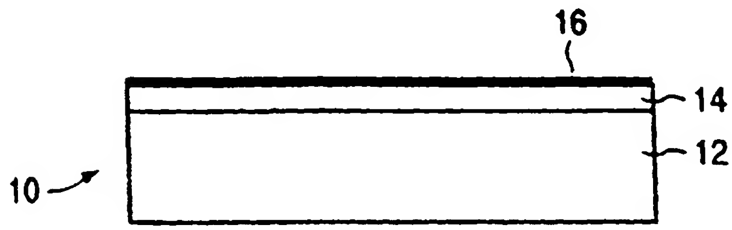


FIG. 1B

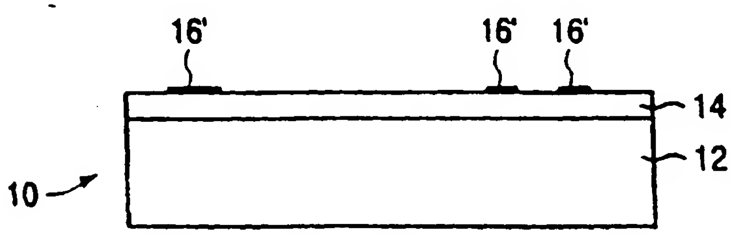


FIG. 1C

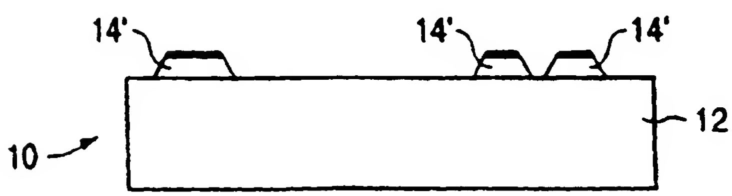


FIG. 1D

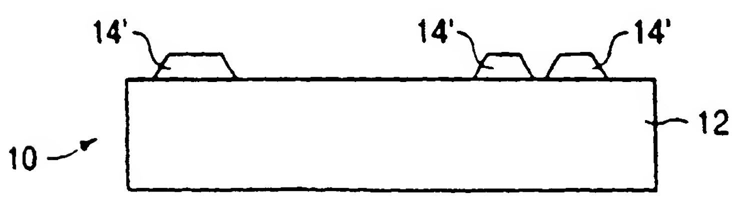


FIG. 1E

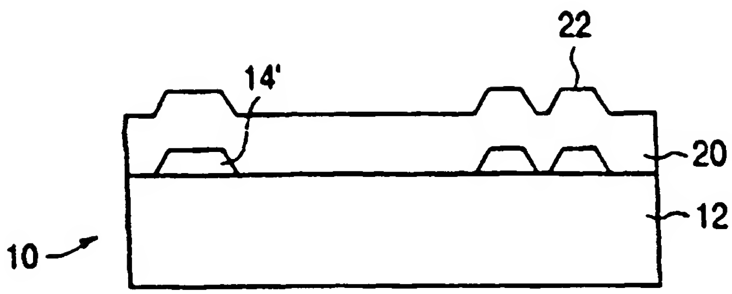


FIG. 2A

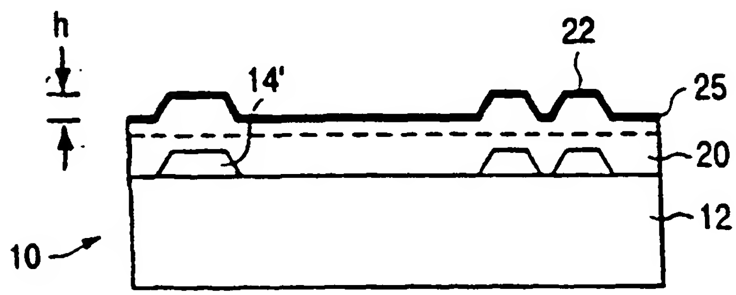


FIG. 2B

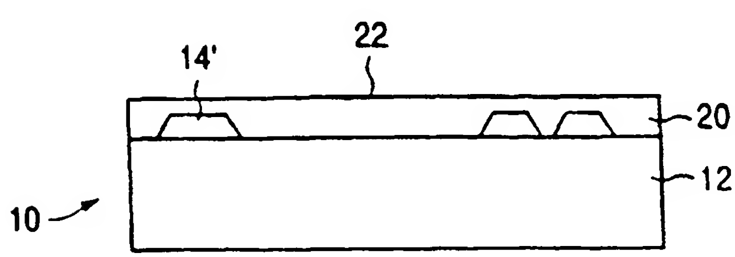


FIG. 2C

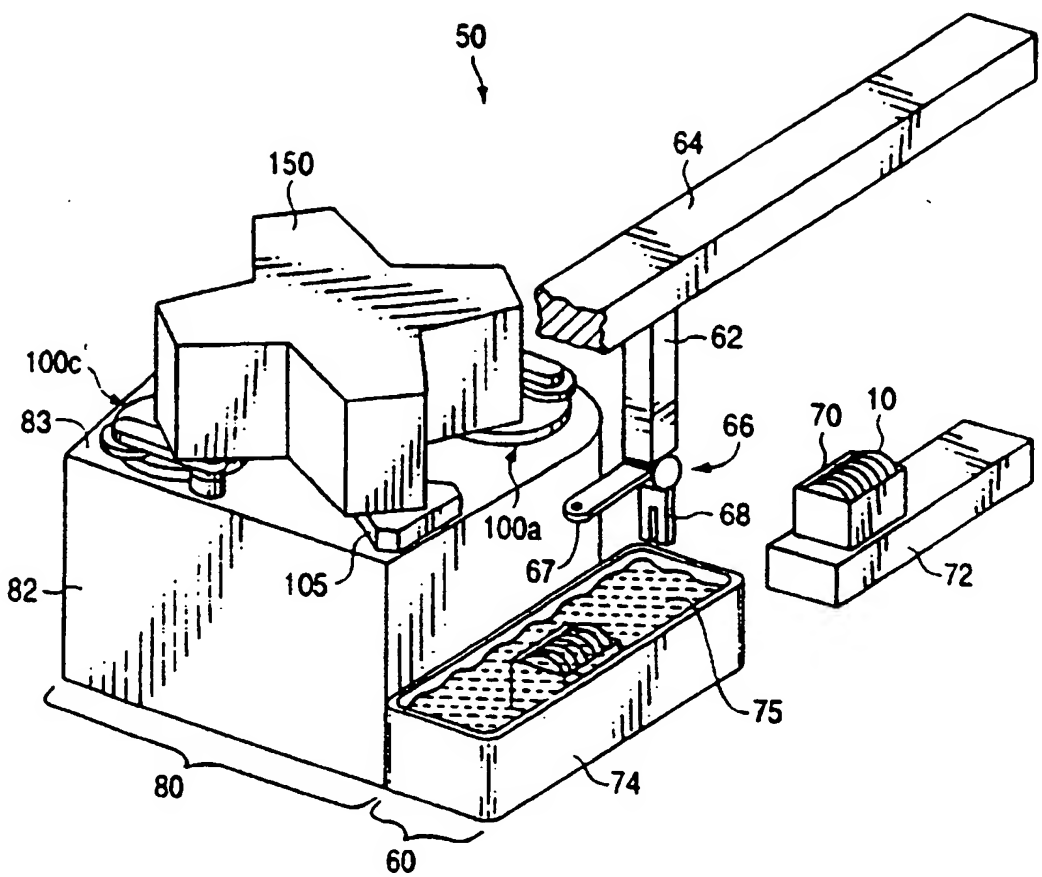


FIG. 3

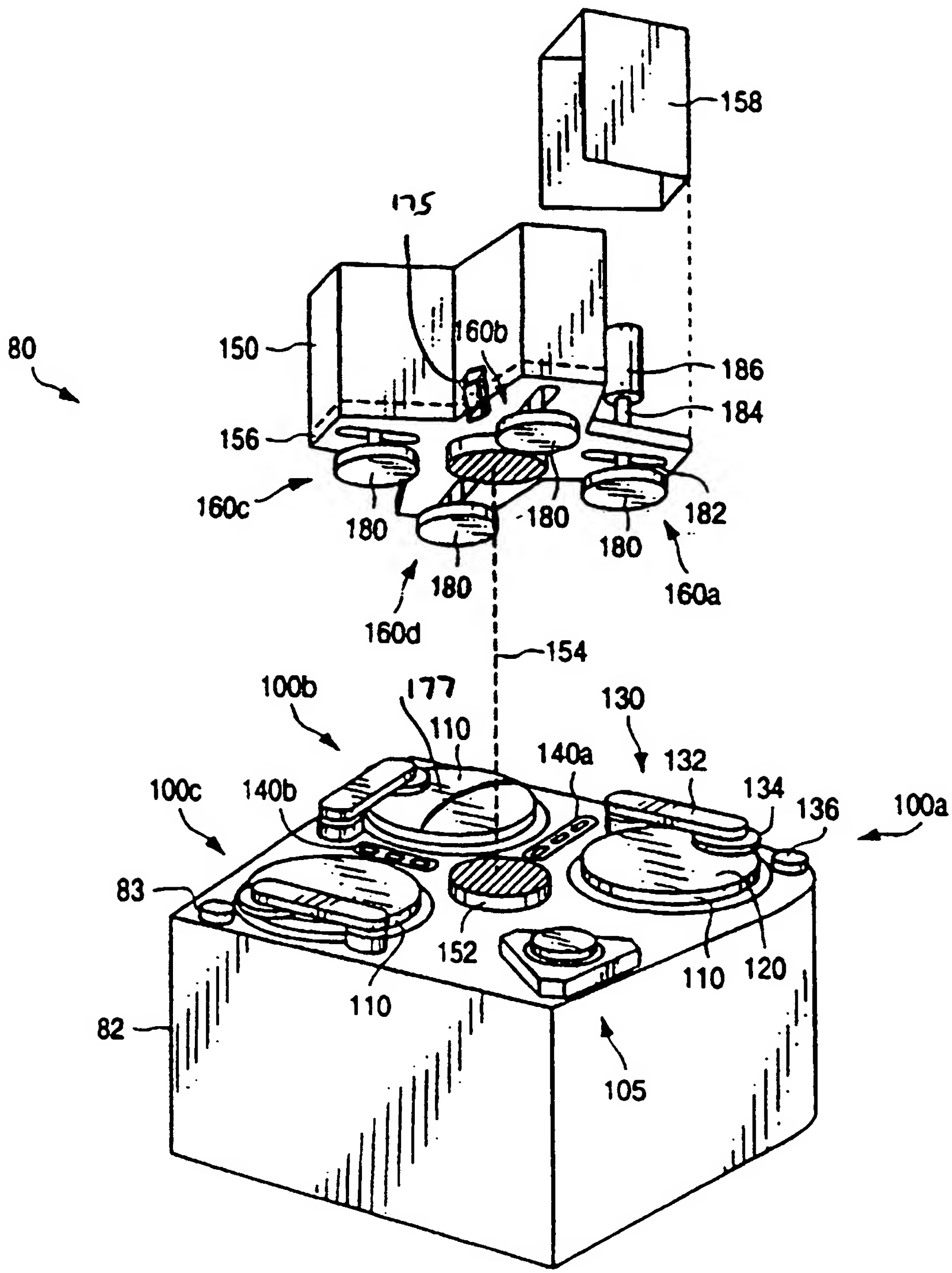

158
175
80
150
160b
186
184
156
182
160c
180
180
180
180
180
160a
160d
154
100b
177
110
130
140a
132
100c
140b
134
136
100a
83
152
110
120
110
82
105

FIG. 4

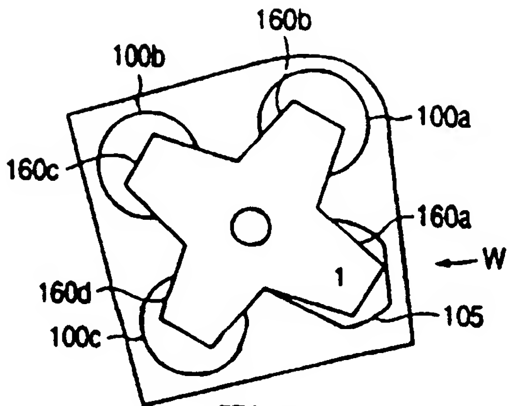


FIG. 5A

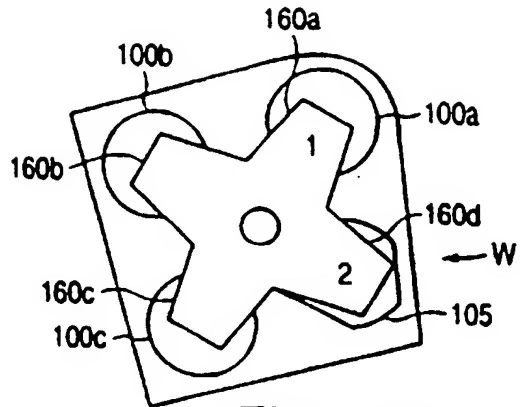


FIG. 5B

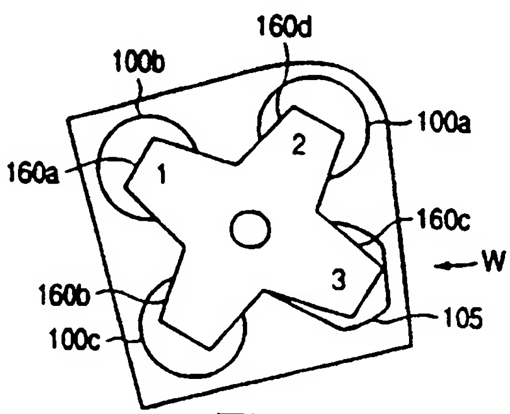


FIG. 5C

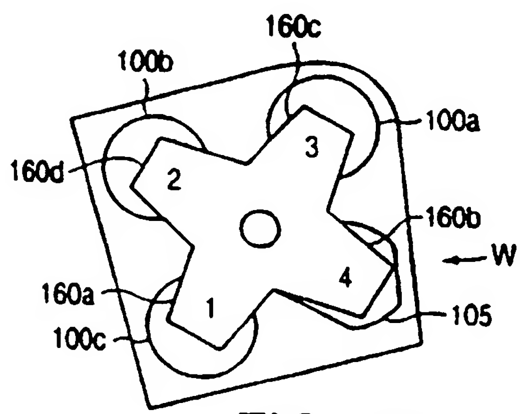


FIG. 5D

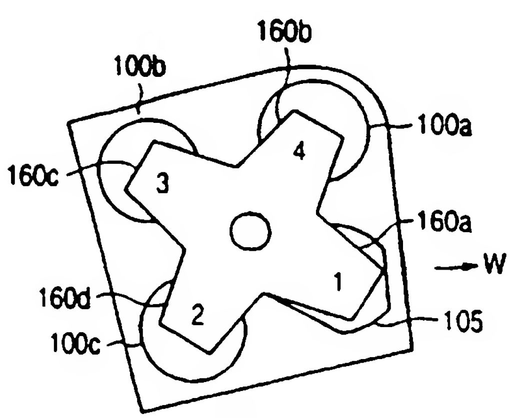


FIG. 5E

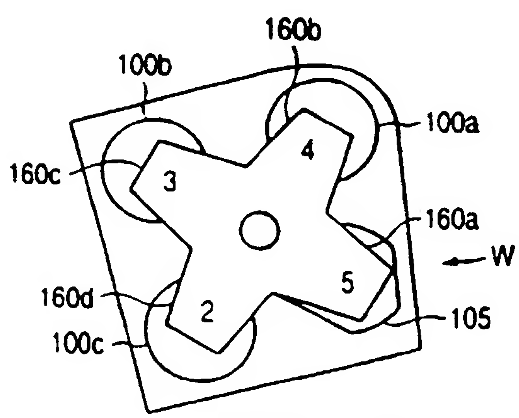


FIG. 5F

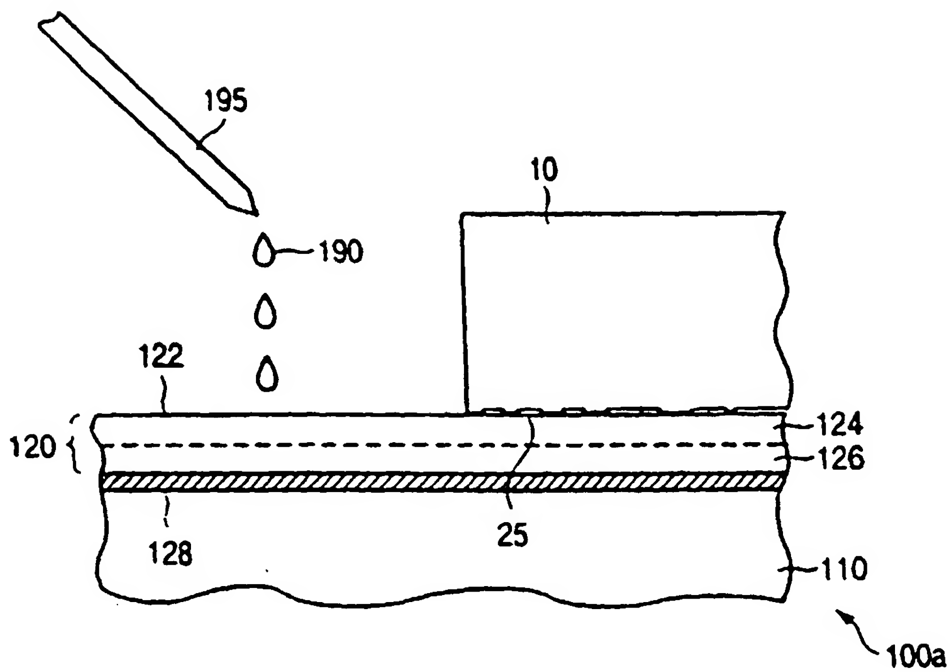


FIG. 6

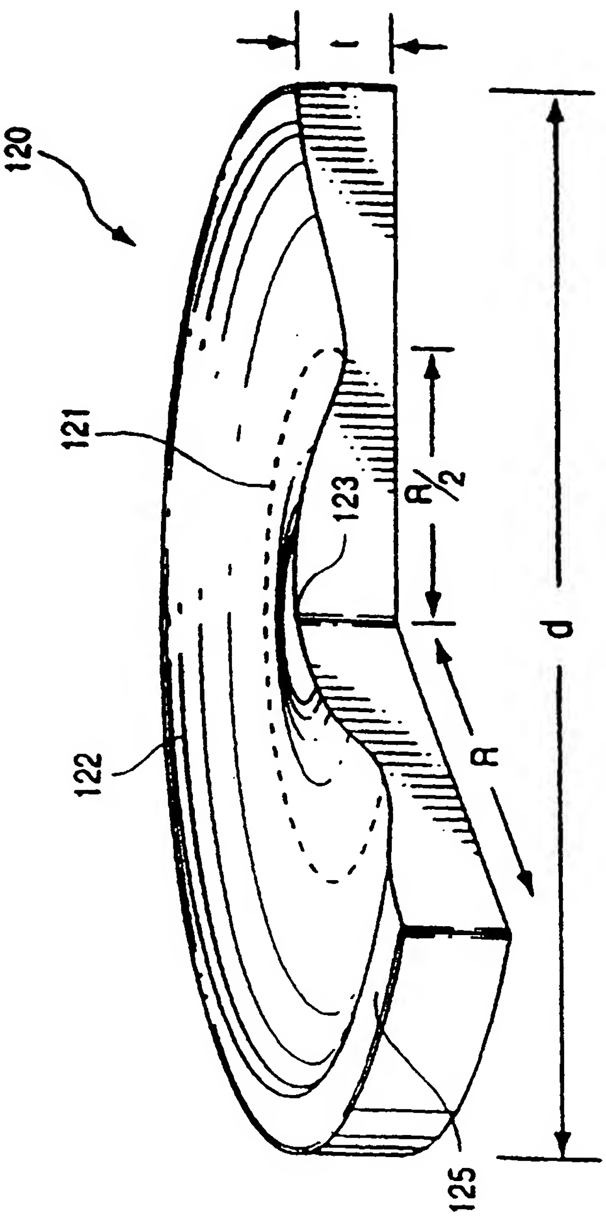


FIG. 7

Fig 8

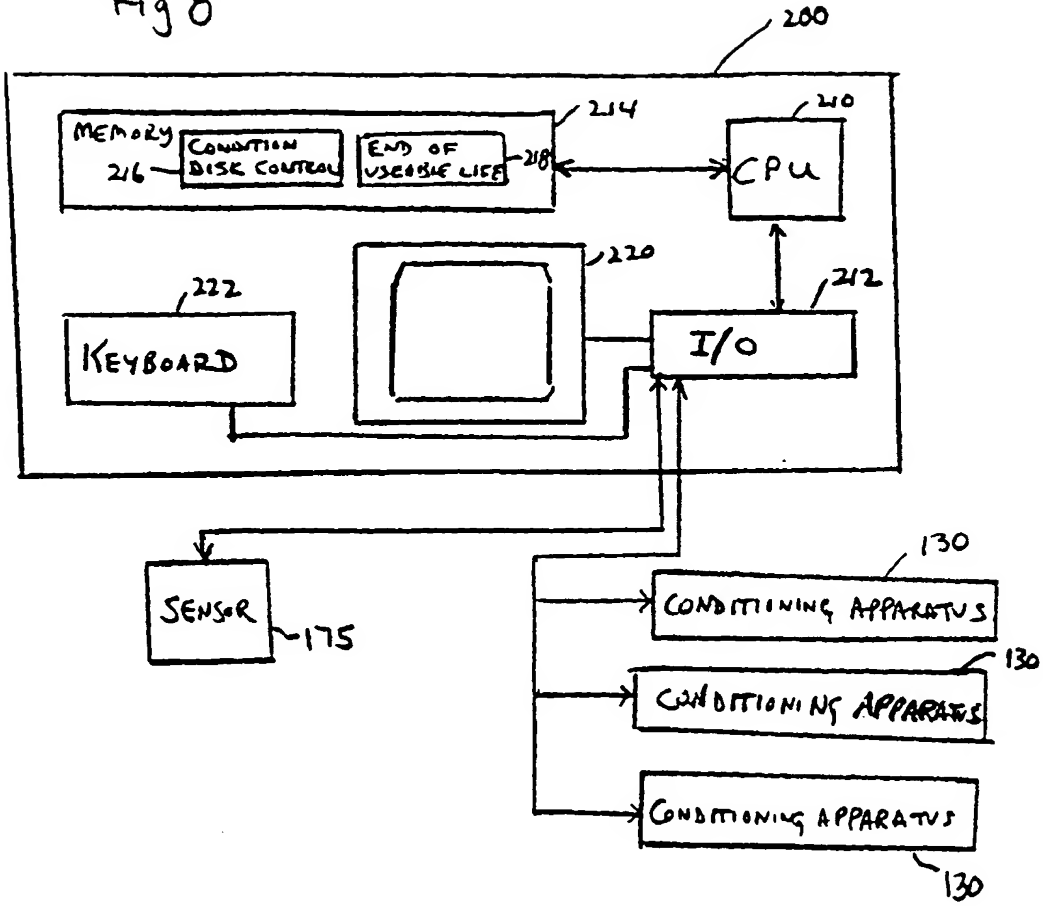
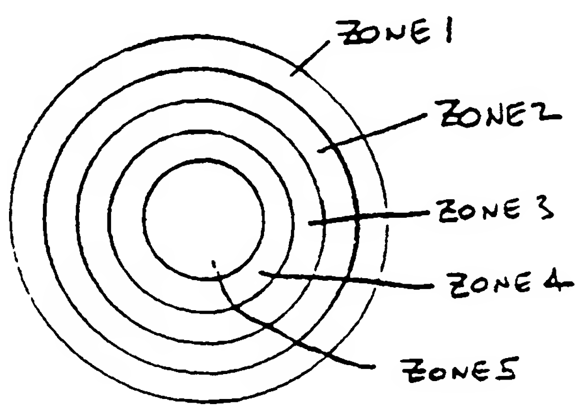

200
MEMORY
CONDITION DISK CONTROL
216
END OF USEABLE LIFE
218
214
CPU
210
220
212
222
KEYBOARD
I/O
SENSOR
175
CONDITIONING APPARATUS
130
CONDITIONING APPARATUS
130
CONDITIONING APPARATUS
130

Fig. 9


ZONE 1
ZONE 2
ZONE 3
ZONE 4
ZONE 5

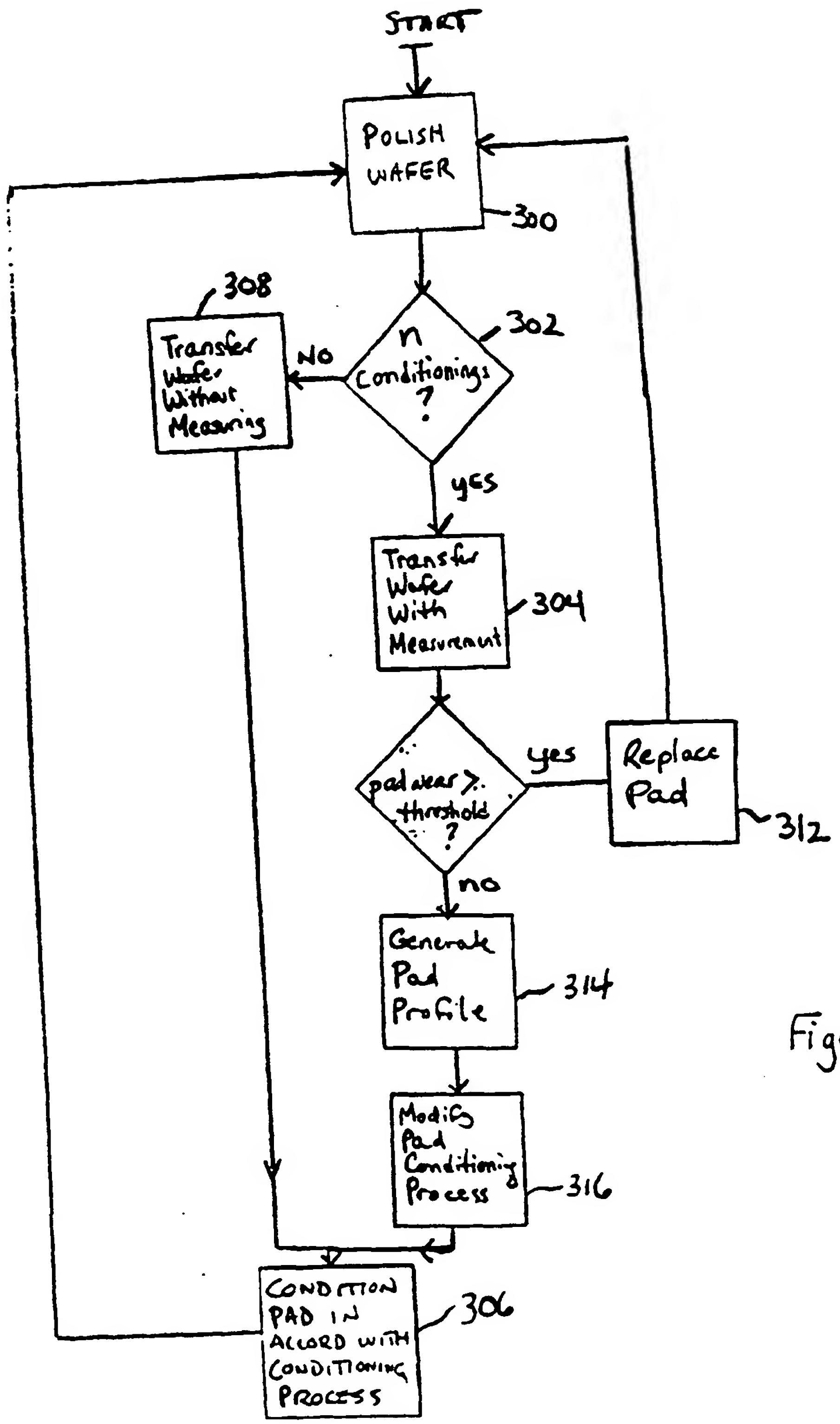

START
POLISH WAFER
300
n Conditionings ?
302
NO
Transfer Wafer Without Measuring
308
yes
Transfer Wafer With Measurement
304
pad wear > threshold ?
yes
Replace Pad
312
no
Generate Pad Profile
314
Modify Pad Conditioning Process
316
CONDITION PAD IN ACCORD WITH CONDITIONING PROCESS
306

Figure 10

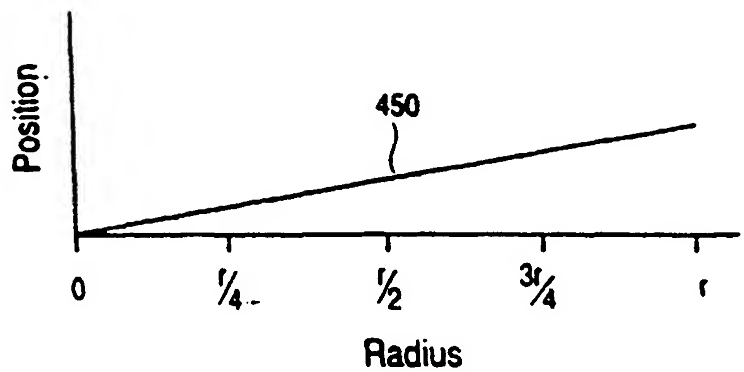


FIG. 11A

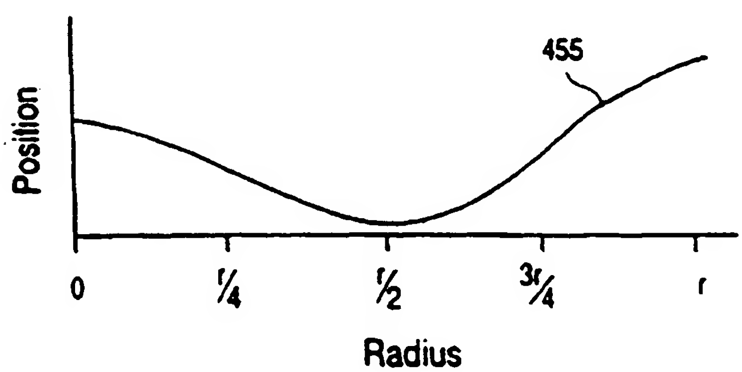


FIG. 11B

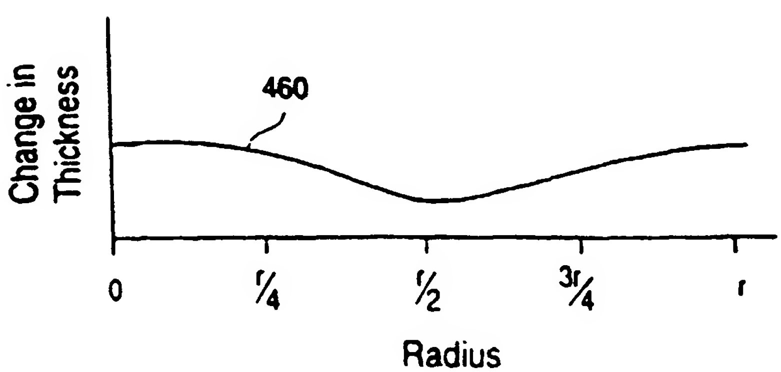


FIG. 11C